High-Frequency Sound Interaction in Ocean Sediments

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LONG-TERM GOALS

Our long-term goals are to develop accurate models for high-frequency scattering from, penetration into, and propagation within shallow water sediments, and to understand the conditions for which objects buried in sediments can be detected acoustically. Reaching these goals requires a better understanding of several fundamental issues pertinent to high-frequency sediment acoustics. These issues include an understanding of the dominant scatterers versus frequency near the sediment surface, the potential need for poroelastic sediment models, the appropriateness of stochastic descriptions of sediment heterogeneity, the importance of single versus multiple scattering in sediments, and an understanding of the physical and biological processes that determine sediment structure.

OBJECTIVES

Our specific objectives include the following: To identify the dominant high-frequency backscattering and subcritical penetration mechanisms, and to demonstrate that these acoustic processes can be quantitatively modeled based on measured sediment properties. To measure sediment attenuation and sound speed over a wide range of frequencies and to use these results, combined with measured sediment properties, to test the validity of sediment acoustic models, and in particular the poroelastic (Biot) model. To measure backscattering levels from buried objects at subcritical grazing angles using synthetic aperture sonar (SAS) measurements in order to test buried-object-detection modeling accuracy.

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APPROACH

The objectives were addressed with a major field experiment designated SAX99 (for sediment acoustics experiment–1999) carried out from late September to mid November 1999 in collaboration with other investigators [1], [2]. The medium sand site was near Fort Walton Beach, Florida, and was chosen to give a relatively high critical grazing angle (about 30°). A well-defined ripple field was present at the SAX99 site with a ripple wavelength of about 50 cm. In addition to acoustic scattering, penetration, and propagation measurements [1], the physical properties and biological processes of the sediment and water column were examined in detail [2]. The results of this work provide the information needed to numerically simulate the acoustic measurements, an important step in improving our understanding of the acoustic processes under study.

Following SAX99, further investigations on the role of seafloor ripples for subcritical buried target detection have been pursued in collaboration with the Coastal Systems Station (CSS) in Panama City, Florida. These measurements have been done with synthetic aperture sonar in a test pond under highly controlled conditions.

SAX99 data/model comparisons indicate that the variation of sound speed with frequency is well modeled by Biot theory, but the variation of attenuation with frequency deviates from Biot theory as the frequency increases [3]. To investigate these Biot predictions under controlled conditions, a laboratory investigation of high-frequency propagation in porous media was initiated in FY02. In the laboratory, the pore fluid can be changed, and thus the fluid viscosity can be changed significantly. As a result, the transition region separating the low and high frequency Biot regimes can be shifted in frequency, allowing stringent tests of Biot sound speed predictions to be carried out in the laboratory.

To pursue further the long range goals and objectives in realistic environments, a new experiment (SAX04) is being planned for the fall of 2004. Most of the topics addressed in SAX99 will be examined again, over a broader frequency range (2–500 kHz) and with other notable advances. In particular, a significant advance is planned for SAS measurements on buried targets. During SAX99 the SAS measurements made by CSS used a towed source/receiver system. A moving source/receiver inevitably leads to unwanted motion effects, which can complicate the analysis and interpretation of the data. Also, it is not possible to tow the system repeatedly over exactly the same path as sediment interface conditions change. To avoid these limitations a 50-m rail system for controlled SAS measurements will be deployed by our group at the Applied Physics Laboratory (APL-UW).

Analysis of SAX99 acoustic penetration data and comparisons with simulations have shown conclusively that scattering from large-scale sediment ripple is the dominant mechanism for subcritical penetration at 10-50 kHz [4]. Thus, during SAX04 it will be essential to characterize the sediment ripple in detail. A new ONR Departmental Research Initiative (DRI) will begin in FY04 and aid in ripple characterization during SAX04. The DRI is titled “Critical Benthic Environmental Processes and Modeling at SAX04” and is also known simply as the Ripples DRI. “The DRI goal is to develop predictive understanding of small-scale ripple morphology and its temporal evolution, including genesis, evolution, and decay, in sandy environments across the inner shelf.” [See call for planning letters, Coastal Dynamics, T. Drake program officer.] The understanding developed through the DRI investigations should increase our ability to make reliable predictions for other environments of acoustic processes dependent on sediment ripple properties.

WORK COMPLETED

Analysis of the primary data sets gathered during SAX99 was completed in FY02 [3]-[9], and during FY03 work was done on several additional topics related to SAX99. A special session on high-frequency sediment acoustics at the spring 2003 Acoustical Society Meeting (Nashville) was organized to provide a venue for final reporting on SAX99 results.

SAX99 backscattering data at 300 kHz were used to test a method for inverting such data for ripple heights. The method was then used to determine unknown ripple heights at the Target Field site near Panama City, where CSS detected buried targets using SAS imaging during SAX99 [1], [9].

During SAX99 data were collected with a new two-dimensional tomographic system called the Acoustic Imager (AI). These data have been analyzed to investigate sound speed variability in the sediment just below the sediment surface.

A problem has persisted in modeling the relatively high coda levels of the buried hydrophones in the SAX99 penetration measurements. Simulations have been used to show that scattering by sediment volume heterogeneity is the likely cause of the coda.

SAX99 measurements show the existence of a transition layer in about the upper 3 mm of the sediment, a region of rapidly decreasing density as the interface is approached [6], [10]. In order to understand the potential impact of this transition layer on acoustic scattering, an analysis of this effect was carried out using a unified approach to volume and roughness scattering that takes into account wave-like volume perturbations within the transition layer and provides the correct low frequency transition from volume to roughness scattering. (Analysis carried out by Anatoliy Ivakin.)

In our work with CSS on subcritical buried target detection under highly controlled conditions, two additional sets of measurements were made at the CSS test pond. Sinusoidal ripple fields were generated by scraping the sand with a machined rake. A silicon-oil-filled steel spherical steel shell was used for the buried target. The ripple profile and the superimposed fine-scale roughness were measured with the second generation version of the APL-UW sediment conductivity probe system (IMP2).

For our laboratory program to test Biot theory and other model predictions of the frequency dependence of sound speed and attenuation in unconsolidated sediments, a second measurement system has been developed to extend the frequency band to 40–260 kHz; the previous range was 80–260 kHz. The results of this work are described under a separate ONR project titled "Acoustic propagation and scattering within sand sediments: Laboratory experiments, modeling based on porous media theory, and comparisons to SAX99 results," B. Todd Hefner, PI.

Preparations for SAX04 are ongoing. Two SAX04 workshops were organized and held during FY03: the first in Cancun, Mexico in December 2002 and the second in Nashville, Tennessee in April 2003. The APL-UW 50-m rail system for controlled SAS measurements is under construction.

In order to simulate the planned rail system SAS measurements prior to SAX04, important for experiment planning, and to prepare for SAX04 data analysis, SAS simulation methods applied to acoustic penetration into sediments are under development. This work is jointly supported by an ONR project titled “Enhancing SAS buried mine detection and long range operation by exploiting the environment,” Kevin L. Williams, PI. Results are described in the report for that project.

RESULTS

Ripple height inversion: Backscattering data taken during SAX99 at 300 kHz show that the bottom backscattering strength is locally modulated by the ripple fields. Furthermore, it was found that when the backscattering data are taken along a direction parallel to the ripple crests, the scattering strength is consistent with Lambert’s law over the grazing angle range of 5°–18° with a Lambert coefficient of –13 dB. To investigate the possibility of inverting the ripple field from backscattering data, a two-scale Monte Carlo simulation model was developed. In the model, the backscatter is assumed caused by random strength scatterers that obey Lambert’s law on average and are randomly distributed on the large-scale ripple field. The local grazing angle with respect to the ripple profile was used to modulate the local Lambertian scattering. In the simulations the backscattering strength is calculated from the known ripple fields, and then the scattering strength is used to invert for the ripple fields as a test. Simulations show that this approach can successfully invert for bottom ripple fields [11]. Simulation experience indicates that the uncertainty for the inverted rms ripple height is about 0.04 cm for the specific area of the ripple patch being inverted, with a tendency to be biased low. Further work is needed to better quantify the uncertainty, but at this point we assume an uncertainty of 0.04 cm also applies to the results quoted below. When this method was applied to 300 kHz SAX99 data, it was found that the inverted ripple heights, as well as the ripple wavelengths, are consistent with physical measurements of the ripple parameters obtained during SAX99. For example, the rms ripple height was found to be 1.15 cm by inverting 300 kHz data, whereas the rms ripple height measured by an APL-UW bottom conductivity system (IMP) was 1 cm. (Inversions potentially offer a major advantage for basic research relative to systems such as IMP or stereo cameras: the ability to cover large 2D regions of the bottom and thereby get a better statistical measure of rms roughness. In Navy applications the advantage would lie in allowing through-the-sensor estimates of rms roughness, a parameter that our research indicates is key to assessing buried mine detection.)

We then applied the inversion technique to SAS data at 180 kHz collected by CSS at the SAX99 site near Fort Walton Beach. Because the CSS SAS system was not calibrated, absolute scattering strengths are not obtained. However, assuming the SAS system is linear, the relative modulation of the scattering strengths can still be used to invert for the ripple field. Figure1 shows an inverted ripple field, which has an rms ripple height of 1.01 cm, consistent with the 300 kHz results and the physical measurements on the ripple field.

We next applied the inversion to SAS data collected by CSS at the Target Field site near Panama City, where there were no direct measurements of the ripple heights, though dive observations indicated that the ripple heights were larger than at the SAS99 site. Figure 2 shows the inversion result for the Panama City site, and the inverted rms ripple height for this case is 1.93 cm. The higher ripple heights inferred for this site may help explain the surprising buried target detections made with the CSS SAS system [9]. [This work is jointly supported by an ONR project titled “Measurement of seabed roughness,” D. Tang, PI.]

Acoustic imager analysis: The AI system takes high-frequency (175 kHz) acoustic transmission data on many crossing ray paths covering a plane, circular area with a diameter of 29 cm. When the AI is pressed into the sediment to a specific depth, two-dimensional estimates of sound speed and attenuation coefficient of the sediment within the circular area can be obtained. Taking data at different depths allows three-dimensional images of the sediment to be obtained. When the same slice of sediment is repeatedly imaged over time at a given depth, the temporal decorrelation of the images can be used to examine changes in the sediment volume due to biological activity. During SAX99, three deployments of the AI were devoted to the study of three-dimensional sediment sound speed and attenuation coefficient to a depth of 12 cm, and one deployment was dedicated to temporal variability with the AI deployed at a depth of 8 cm for 65 hours, taking images every hour.

The sound speed was found [12] to increase by 20 m/s over the top 10 cm of sediment, with random sound speed variations in the range of 0.5–1.0%. No depth dependence in the random variations is observed after mean gradient is removed. The AI data were used to estimate a one-dimensional power spectrum of sound speed variability, which was found to be consistent with the corresponding density variability spectrum obtained from the bottom conductivity system (IMP). Finally, no temporal decorrelation in sound speed structure is evident in the 65 hour data record.

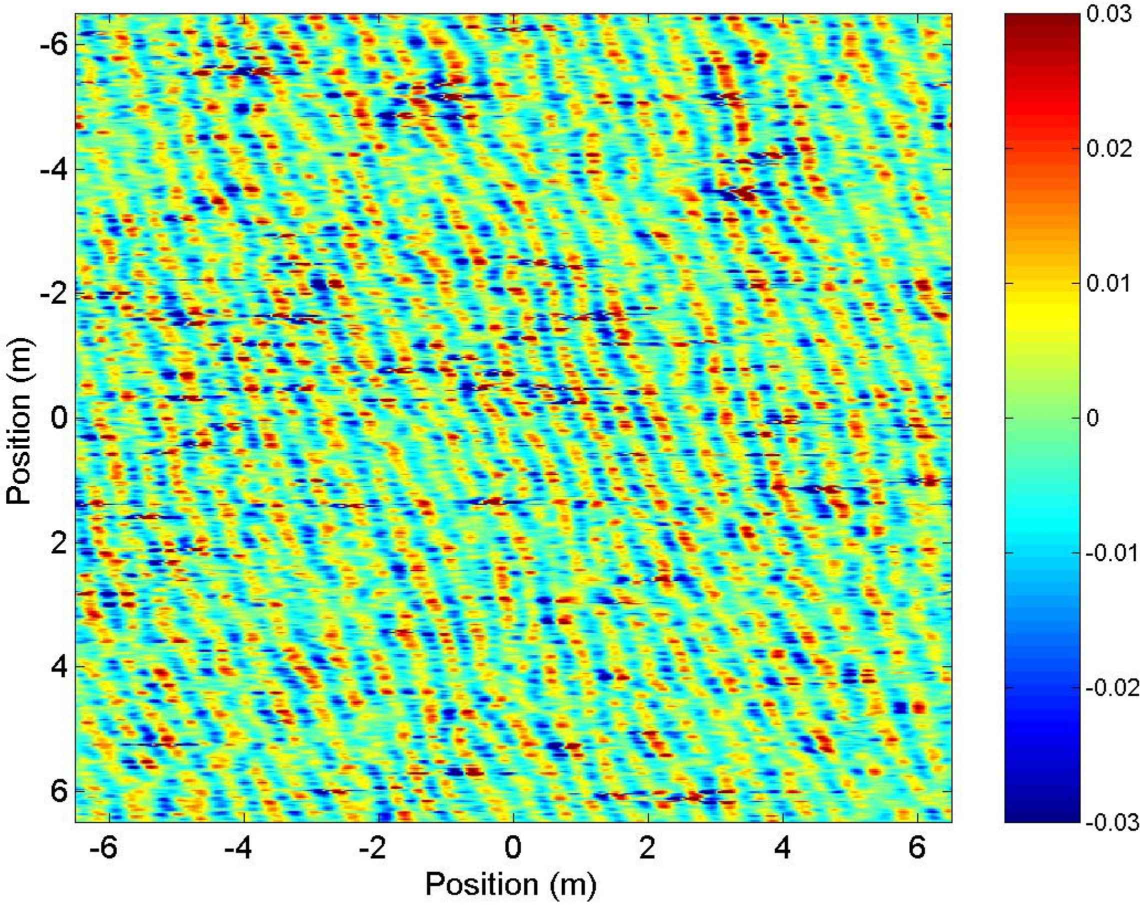

Figure 1. Ripple field inverted from 180 kHz backscattering data taken at the SAX99 site near Fort Walton Beach, Florida. The color bar denotes ripple height in meters relative to the mean plane.

Buried hydrophone coda: During SAX99 a buried array was used to measure the sound field in the sediment due to sources in the water column over the frequency range of 11–50 kHz. The sound field at the array showed a coda that was longer and higher than suggested by simulations of rough-interface scattering. The volume scattering strength has been estimated by fitting a point scatterer model to the coda data, and the strongest discrete scatterers have been located and characterized by backpropagation of the buried hydrophone data [13]. A large discrete scatterer with target strength of –23 dB was identified at a depth of about 5 cm. When the measured properties of the volume scatterers are inserted in backscattering models, the predicted backscattering strengths fall somewhat below measured values, indicating that roughness scattering is dominant for backscattering at this sandy site, yet the results are still consistent with volume scattering being dominant for producing the coda at the buried hydrophones. The results also indicate that the coda can be used to obtain the frequency dependence of the volume scattering strength.

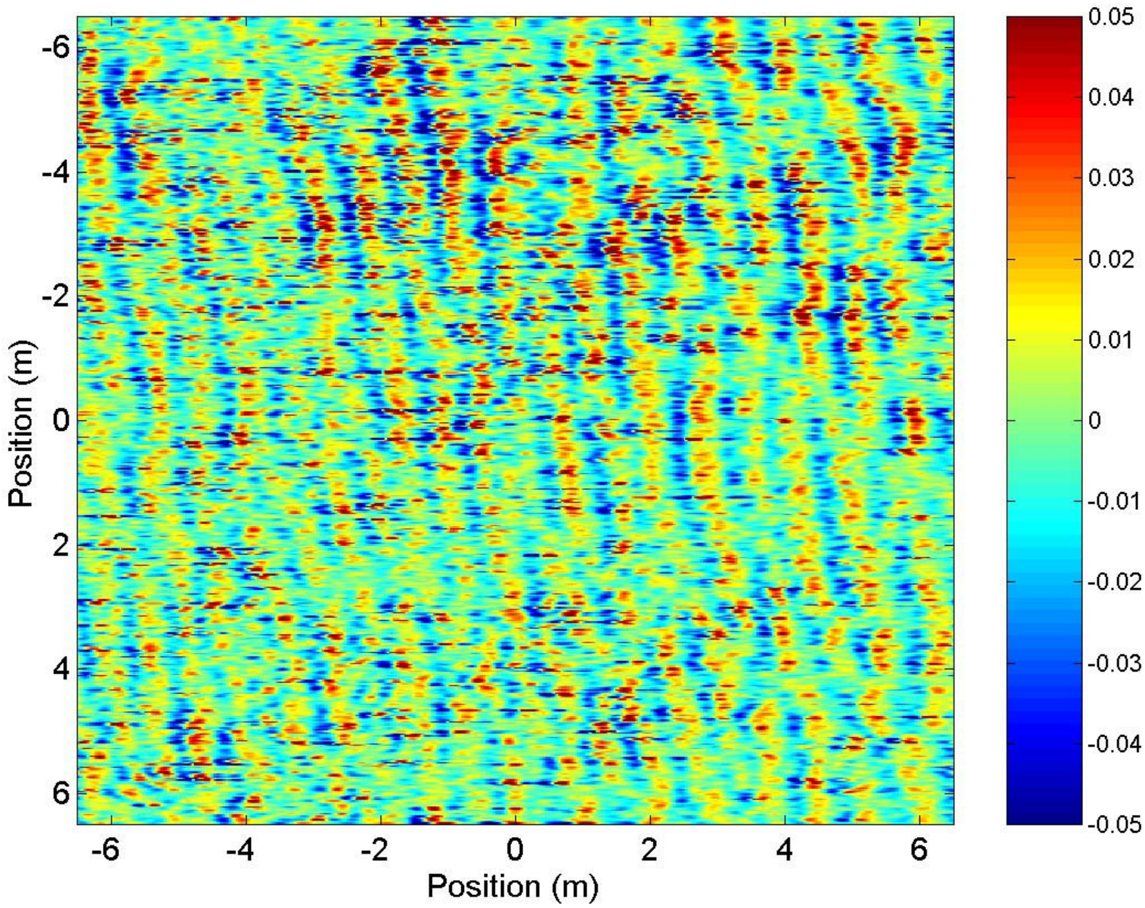

Figure 2. Ripple field inverted from 180 kHz SAS backscattering data taken at the Target Field site near Panama City, Florida. The color bar denotes ripple height in meters relative to the mean plane.

Effect of transition layer on rough interface scattering: The result of Ivakin's analysis is that the frequency would need to be on the order of 250 kHz before the transition layer would significantly affect rough interface scattering. At these frequencies, however, acoustic measurements suggest that volume scattering dominates interface scattering [5]. Therefore, transition layer effects should be negligible for roughness scattering for the sediment conditions encountered in SAX99.

Subcritical buried target detection: Subcritical buried target detections were made at the CSS test pond with rms ripple heights of about 2.5 cm and ripple wavelengths of 75 cm [14] extending previous work

[15]. The backscatter level from the target was found to be higher than predicted using first-order perturbation theory to model ripple scattering at a grazing angle of 20°, at frequencies of 20–40 kHz, and when the target is located under a ripple crest. This shows that under some conditions higher-order scattering effects may contribute significantly to target detections. These results are likely related to the surprising buried target detections made during SAX99 with the CSS SAS system [9]. [This work is jointly supported by an ONR project titled "Measurement of seabed roughness," D. Tang, PI.]

IMPACT/APPLICATIONS

Work under this program should lead to improved high-frequency models for acoustic scattering from sediments, for penetration into sediments, for propagation within sediments, and for modeling the detection and classification of buried objects. A corollary to acoustic model refinement should be a better understanding of the essential parameters that are needed for practical models.

RELATED PROJECTS

1. Title: Measurement of seabed roughness, Grant# N00014-02-1-0008, D. Tang, PI. This project supports a collaborative experimental effort between CSS and APL-UW focused on controlled measurements of buried target detections in a test pond at CSS. APL-UW has deployed a bottom-mounted conductivity measurement system (IMP2) to measure interface roughness above the buried target. This grant also partially supports our work on acoustic inversion of ripple field properties.

2. Title: Enhancing SAS buried mine detection and long range operation by exploiting the environment, Grant# N00014-03-1-0772, K. L. Williams, PI. The goal of this project is to develop robust simulation techniques that can be applied to SAS buried target detection. This grant partially supports our simulation development associated with planned rail system SAS measurements in SAX04.

3. Title: Acoustic scattering from heterogeneous rough seabeds, Grant# N00014-01-1-0087, A. N. Ivakin, PI. This project is focused on improving understanding of scattering from seabed roughness and volume heterogeneity, central elements of SAX99 and SAX04 measurements. In particular, scattering from shell fragments and other discrete inclusions is being modeled under this program, and the results will likely have important applications in SAX04 analysis.

4. Title: Acoustic propagation and scattering within sand sediments: Laboratory experiments, modeling based on porous media theory, and comparisons to SAX99 results, Grant# N00014-02-1-0336, B. T. Hefner, PI. This postdoc grant supports much of our laboratory program to test Biot theory and other model predictions of the frequency dependence of sound speed and attenuation in unconsolidated sediments.

5. Title: Environmental complexity and stochastic modeling of high frequency acoustic scattering from the seafloor, Grant# N00014-02-1-0341, C. D. Jones, PI. A digital stereo photography system is being developed under this grant and will be used for sea floor roughness characterization during SAX04.

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PUBLICATIONS

The first seven publications listed below first appeared in October 2002 in an IEEE-JOE Special Issue that was nominally dated July 2002.

D. R. Jackson, K. L. Williams, E. I. Thorsos, and S. G. Kargl, “High-frequency subcritical acoustic penetration into a sandy sediment,” IEEE J. Ocean. Eng. **27**, 346-361 (2002). [published, refereed]

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